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Lossy Magnetic Energy Storage Inductor-Converter Unit as a Lead-Lag Var Compensator

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ABSTRACT

The 12-pulse converter-bridge associated with a Lossy Magnetic Energy Storage (LMES) unit has a certain freedom in choosing the reactive power consumption. Utilizing this Q-modulation capability of the converter, LMES unit can act as a continuous Var controller while acting as a load frequency stabilizer at the same time. The converter is operated under two-quadrant mode, in equal-α mode of operation. Under two-quadrant mode of the converter, LMES unit can provide leading Var and lagging Var, as necessary using the switched capacitor bank following a load voltage deviation. In this paper, a comprehensive control strategy to achieve the reactive power modulation has been formulated and applied in the test network in a single area power system and shows the effectiveness of the LMES unit for the improvement of power system dynamics. It is found that the proposed mode of control greatly improves the overall performance of the Q-V loops as well as the P-f loops of a power system.

Keywords: Energy Storage, Lossy Magnet, Reactive power control, and Equal-α mode.

1. INTRODUCTION

Power system oscillations occur when there are system disturbances such as sudden small load perturbations or faults, which continuously disturb the normal operation of a power system. The damping of the system must be such that the synchronous generators can return to their steady state conditions after the disturbances [1]. Especially when the load-end of the transmission line experiences sudden load perturbations, the generators need continuous control to suppress undesirable oscillations in the system.

In power systems, continuous reactive power compensation in the load end of transmission lines is generally required for static and dynamic voltage control and system stability preservation [2]. Shunt capacitors, shunt reactors, series capacitors and synchronous condensers have been used for this purpose for many years. In substations where the nature of load requires high speed of response, a continuous reactive power adjustment ability, the static Var systems (SVS), only of fixed capacitor, thyristor-controlled-reactor (FC-TCR) type have been used as a viable and desirable option. The purpose of the present paper is to show that LMES units, while acting as load frequency stabilizer, can also perform the role of a continuous Var controller.

When operating in the continuous current mode, the 12-pulse bridge converter of the LMES unit [3] creates a phase difference between the input voltage and fundamental component of current waveform and hence always draws lagging Var. The amount of reactive power consumption depends on the firing angle of the two-cascaded 6-pulse converters. This Q-consumption can be used to advantage for accurate control of lagging Var by operating the converter in equal-α mode. In this mode the firing angles of the two 6-pulse bridges are controlled to give freedom in selecting the Var consumption at any point of active power transfer.

To achieve a complete Var control, covering the leading and lagging Var regions, a 3-ϕ capacitor bank of suitable rating is placed across the terminals of the LMES unit. Due to the inherently limited Var control range of the 12-pulse converter, 3-ϕ switched capacitor banks of lower ratings rather than a single 3-ϕ bank, can be used to give continuous and wide range of overall Var modulation capability. With proper control, the LMES unit capacitor bank combination performs the vital role of a continuous Var compensator, while acting as a load frequency stabilizer at the same time. Thus LMES units, if located in load-end substations, would obviate the use of any additional SVS. The schematic diagram of the proposed scheme is shown in Fig. 1.

2. V_{ar} MODULATION CAPABILITY OF THE CONVERTER

In the present mode of control the Var modulation range of the converter, at any instant of time, is constrained by the active power transfer and the current through the inductor. According to the theory of converter operation [4], the voltage E_{di} in the dc side in presence of the source inductance, due to each constituent 6-pulse converter is given by,

$$E_{di} = E_{d0} \cos\alpha_i - R_c I_d \quad (1)$$

Where, E_{d0}: Ideal no-load maximum direct voltage of the 6-pulse bridges

α : Converter firing angle

I_d : Inductor current, and

R_c: Equivalent commutating resistance due to the source inductance [4].

The subscript 'i' identifies the 6-pulse converter number 1 or 2.

Then,

$$P_{di} = E_{d0}.I_d.\cos\alpha_i - Id^2.Rc \quad (2)$$

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Where, P_{di} is the active power transfers through bridge i. This gives the equation for the input power factor as

$$\cos\phi_i = \cos\alpha_i - I_d.R_c/E_{d0} \quad (3)$$

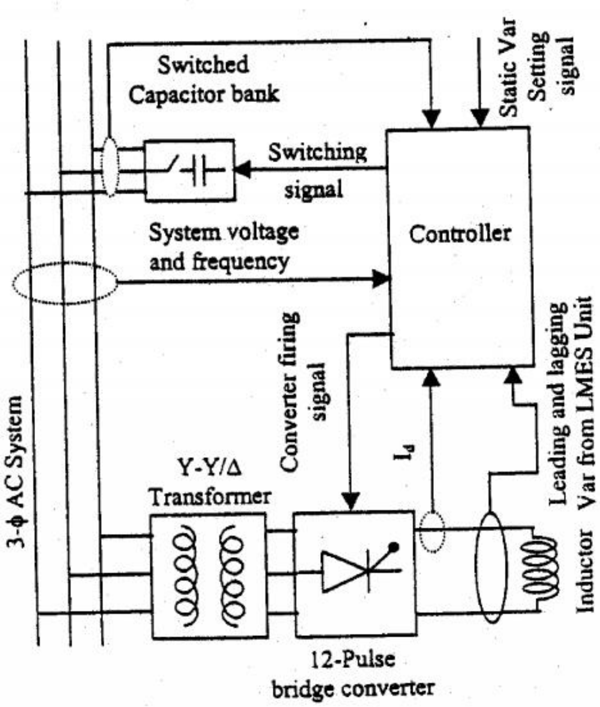

Fig. 1: The schematic diagram of the scheme

The active and reactive power loads presented by the 12-pulse converter under equal-α mode are expressed (neglecting R_c) as

$$P_d = 2E_{d0}\, I_d \cos\alpha \quad (4)$$

$$Q_d = 2E_{d0}\, I_d \sin\alpha \quad (5)$$

The P-Q modulation ranges of a 12-pulse converter, calculated from equation (2), (4) and (5) are shown in fig. 2. These have been drawn by assuming that the firing angle of each converter lies between 5^0 and end stop limit of 165^0. For any value of P, the freedom in choosing the Q is indicated by the difference between the maximum and minimum Q points on that P-line. The actual P-Q point can be located anywhere inside the closed region. For a particular value of I_d maximum P_d is obtained at $\alpha=5^0$ and minimum P_d at $\alpha=165^0$. The Var modulation shows that the maximum Q_d can be obtained in equal α mode (when $\alpha_1=\alpha_2$). For a particular value of P_d if the desired value of Q_d falls outside the available area, it is restricted to the nearest point of the boundary of the curve. It is desirable to set the rated inductor current I_{d0} such that the maximum allowable energy absorption equals the maximum allowable energy discharge [5]. This makes the LMES unit equally effective in damping swings caused by sudden increase or decrease in load. When the inductor current reaches either of these limits, the P_d-Δf control loop is discontinued till the frequency deviation swings to the other side.

Figure 2(a) shows that R_c does not modify the overall Q-modulation range, but it only rotates the loci for maximum and minimum Q in the counterclockwise direction. This increases the Q-modulation range in the inverter region and decreases that in the rectifier region. It is observed from Fig. 2(b) and 2(c) that the increase in I_d and E_{d0} results in larger radii of the semicircular loci, and hence increases the Q-modulation capability.

As the LMES unit is primarily used for load-frequency control, P_d and I_d varies continuously due to the active power modulation. Hence the available Q-modulation range of the converter changes continuously. However, the voltage fluctuation in the system side rarely assumes a magnitude sufficient to have appreciable effect on converter operation. Therefore, once the converter input transformer ratio is selected, E_{d0} can be assumed to remain constant.

3. SYSTEM MODELING

The study of the effects of simultaneous modulation of active and reactive power on power system dynamic performance requires a power system model coupling the active power-frequency and reactive power-voltage loops. The following assumptions are made in the system modeling [9]:

1. The reheat turbine type thermal plant supplies to a single generator whose capacity is 2000MW.
2. The generator is equipped with automatic voltage regulator (AVR) with stabilizing speed feedback.
3. The generator is cylindrical rotor type and the resistances of the generator and the line are negligible in comparison with the reactances.
4. Strong coupling is present between P-f and Q-V loops.

4. THE V_{ar} CONTROL STRATEGY FOR ON-LINE OPERATION OF LMES UNIT

The proposed controller of the LMES unit performs its task by receiving the measured values of area control error, bus voltage deviation, inductor current deviation, Var setting of the capacitor bank and the static Var setting signal coming from the power system control centre.

At any instant of time the reactive power modulation range is calculated from the values of P_d and I_d. A reactive power demand signal is generated from the bus voltage deviation ΔV_L and the static Var setting signal Q_S following the equation:

$$Q_{demand} = Q_s + K_V.\,\Delta V_L \quad (6)$$

where, K_V is the gain corresponding to the voltage deviation. The actual reactive power consumption of the converter is varied continuously depending on the Q_{demand} signal while keeping within the Q-modulation range. When the required Q setting reaches the limits, the adequate switching signal is sent to the capacitor bank so that the required reactive power setting of the converter remains with in the available range.

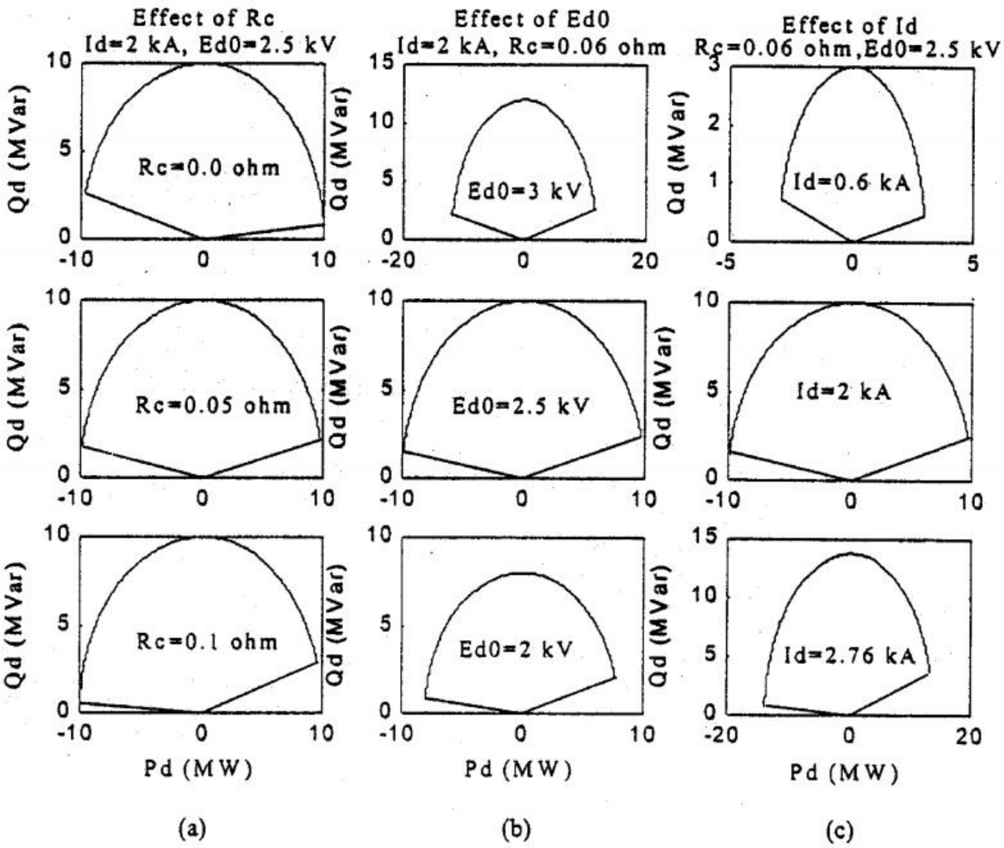

Fig. 2: The P-Q modulation ranges of the 12-pulse converter associated with the LMES unit

5. EFFECT OF PROPOSED P-Q CONTROL

In this section, the effects of the proposed V_{ar} control method have been demonstrated with the help of a simple single area system. The purpose is to show the behaviour of the LMES unit under the control scheme. The magnitude of its impact on the power system would depend on the type of power system and the nature of load.

The effect of Q-modulation is appreciable only when the LMES unit is placed at the load end of a transmission line, sufficiently distant from the generator bus. For this reason, the single area power system shown by the single line diagram in Fig. 3 is chosen for study.

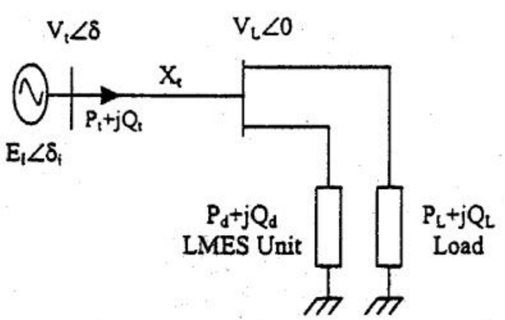

Fig. 3: Single line diagram for test network.

Non-linear dynamic equations are used in the solution process. They are solved using 4[th] order R-K method.

To show the effects of the suggested mode of control, the representative case (load change of 0.008+j0.008 p.u.) study was conducted on the system.

The load voltage deviations of the power system with and without LMES unit is shown in Fig. 4 for the case. The maximum deviation of the load voltage is 0.008 p.u. without LMES unit. After the oscillatory period, the voltage deviation shows a tendency of stabilizing at 0.004 p.u. These oscillations are mainly due to the assumed strong coupling between the P-f and Q-V loops. Figure shows the case when the converter employs the equal-α mode of control.

In the case, the P-modulation by the LMES unit reduces the oscillation in the frequency and Q-modulation improve the load voltage profiles. However, in the case of equal-α mode of control, the inadvertent Q-modulation has no effect on the steady state voltage deviation and only marginal effect on the maximum voltage deviation.

In contrast, Fig. 4 also show that throughout the considered time period, the deviation of the net reactive power Q_{net} supplied by the LMES unit (with switched capacitor bank) follows the load voltage deviation and this Q-modulation substantially reduces ΔV_L. In this case the steady state and maximum voltage deviations are 0.0011 p.u. and 0.0025 p.u. respectively. During the dynamic variation in load voltage,

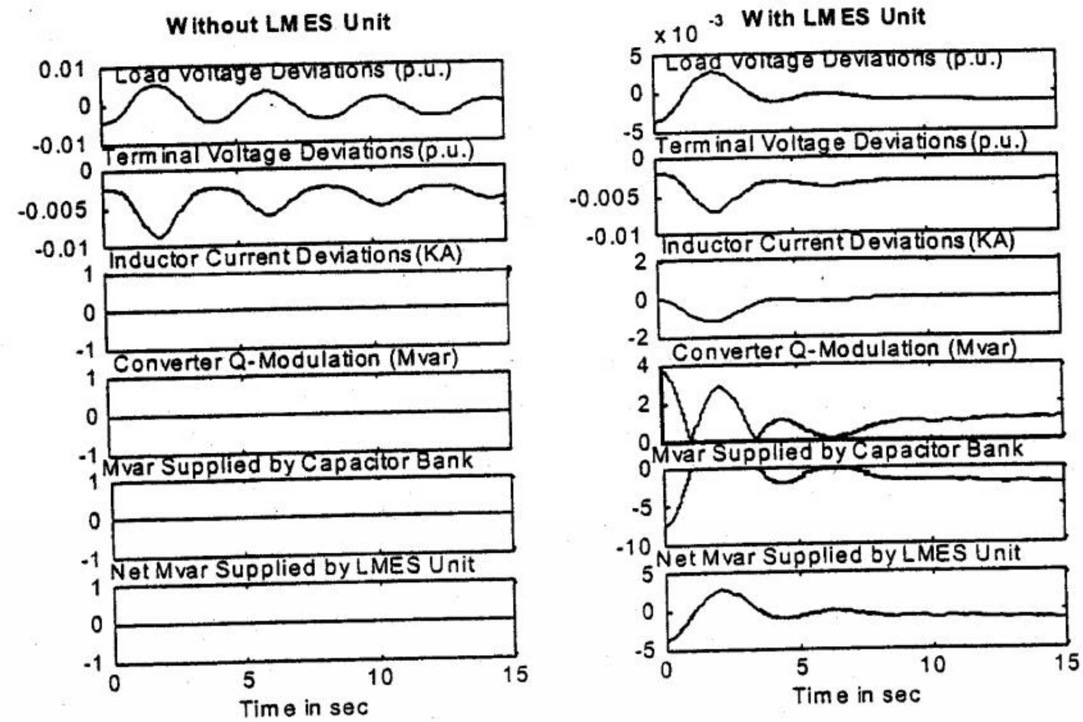

Fig. 4: Response of the power system with and without LMES unit [Load change of 0.008+j0.008 p.u.]

Q_d undergoes quick fluctuation within the Q-modulation range and there is switching of capacitors. The combine effect of these two is the smooth and continuous variation of Q_{net} as seen in this figure.

The range of modulation of Q_{net} depends on the rating of the capacitor bank, and the value of the gain K_V. These two parameters should be chosen according to the voltage characteristics of the bus to which the unit is connected. The capacitor step size should be slightly less than the minimum Q-modulation range of the converter.

It is evident from the Fig. 4 that the controller can provide good compensation with less deviation of inductor current. This ensures the effective use of its power modulation.

With the help of LMES unit along with the switched capacitor bank, the Q_{net} supplied by LMES unit substantially reduces the voltage deviation. In Fig. 4, it is observed that due to fast AVR action, the load-voltage goes up within a few seconds. When operated in the two-quadrant mode, the LMES unit itself absorbs inductive Var in addition to ΔQ_L due to sudden load application. Therefore switching of static capacitors is needed during the dynamic variation of the load voltage. With four-quadrant operation the amount of switching capacitance needed is much less than that of two-quadrant operation. But it has no advantage on P-modulation in four-quadrant mode.

6. CONCLUSIONS

This paper shows that Lossy Magnetic Energy Storage units can simultaneously operate as continuous Var controller while performing the role of load-frequency stabilizers in electrical power systems. This is achieved by operating the converter in equal-α mode with a switched capacitor bank placed across its terminals.

The P versus Q modulation ranges of the 12-pulse converter depends on the source inductance, secondary voltage of the input transformers, and the output current. Once the input transformer is chosen then the Q-modulation range depends on the active power transfer and the current through the inductor at any instant of time. The actual reactive power consumption of the converter is varied continuously depending on the requirement of the power system while keeping within the Q-modulation range. Switching of the capacitor bank keeps the required Q-consumption of the converter within the available range.

It has been shown that this mode of control improves the overall performance of the power system in Q-V loop and obviates the use of any additional Var compensator in the power area where the LMES unit is needed.

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APPENDIX - I [8]

System Parameters

Area capacity P_R = 2000 MW, Base MVA=2000.
Nominal loading =1000 MW at 0.9 p.f. Lagging.
Nominal load-end voltage = $1.0 \angle 0^0$ p.u.
f^0 = 50 Hz, X_d = 1.0 p.u., X_d' = 0.25 p.u., X_t = 0.3 p.u., H = 5.0 s, R = 2.4 Hz / p.u. MW, K_0= 150.0 Hz / p.u. MW, K_r = 0.5, T_p = 20.0 s, T_T = 0.3 s , T_G = 0.08 s, T_r = 10.0 s, K_I = 0.8, T=0.06s, T_{d0}=5.9s.

LMES Unit

S_{max} = 10 MVA, L = 3.0 H, I_{d0} = 2 kA, E_{d0} = 2.5 kV, R_C = 0.02, R_L=0.05 Ω and T_{dc}=0.026 seconds.